

# On the population of primordial star clusters in the presence of UV background radiation

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## ABSTRACT

We use the algorithm of Cole et al. (2000) to generate merger trees for the first star clusters in a  $\Lambda$ CDM cosmology under an isotropic UV background radiation field, parametrized by  $J_{21}$ . We have investigated the problem in two ways: a global radiation background and local radiative feedback surrounding the first star clusters.

Cooling in the first halos at high redshift is dominated by molecular hydrogen,  $H_2$ —we call these Generation 1 objects. At lower redshift and higher virial temperature,  $T_{\text{vir}} \gtrsim 10^4 \text{ K}$ , electron cooling dominates—we call these Generation 2.

Radiation fields act to photo-dissociate  $H_2$ , but also generate free electrons that can help to catalyse its production. At modest radiation levels,  $J_{21}/(1+z)^3 \sim 10^{-12} - 10^{-7}$ , the nett effect is to enhance the formation of Generation 1 star-clusters. At higher fluxes the heating from photo-ionisation dominates and halts their production. With a realistic build-up of flux over time, the period of enhanced  $H_2$  cooling is so fleeting as to be barely discernable and the nett effect is to move primordial star cluster formation towards Generation 2 objects at lower redshift.

A similar effect is seen with local feedback. Provided that enough photons are produced to maintain ionization of their host halo, they will suppress the cooling in Generation 1 halos and boost the numbers of primordial star clusters in Generation 2 halos. Significant suppression of Generation 1 halos occurs for specific photon fluxes in excess of about  $10^{43} \text{ ph s}^{-1} M_{\odot}^{-1}$ .

**Key words:** galaxies: formation – galaxies: star clusters – stars: Population III

## 1 INTRODUCTION

Primordial star clusters contain the first stars to form in the Universe, from zero-metallicity gas. Previous work (e.g. Tegmark et al. 1997; Abel et al. 1998; Hutchings et al. 2002; Bromm et al. 1999; Santoro & Thomas 2003) has concentrated on the very first objects for which there is no significant external radiation field. However, these first clusters are expected to produce massive stars which will irradiate the surrounding Universe and may well be responsible for partial re-ionisation of the intergalactic medium.

The only species produced in sufficient abundance to affect the cooling at early times is molecular hydrogen. Its presence allows the first objects to cool and form in low temperature halos ( $T < 10^4 \text{ K}$ ) at high redshift ( $z_{\text{vir}} \sim 20 - 30$ ). However, molecular hydrogen is very fragile and can easily be dissociated by UV photons in the Lyman-Werner bands, (11.2 – 13.6 eV). Thus, the formation of the first stars may

well have a negative feedback effect on subsequent population III star formation by suppressing cooling via this mechanism. This problem is not a trivial one and has been the subject of much interest in recent years (e.g. Haiman et al. 1996; Haiman et al. 2000; Kitayama et al. 2000; Glover & Brand 2001; Omukai 2001; Machacek et al. 2001; Ricotti et al. 2002; Oh & Haiman 2002; Cen 2003; Ciardi et al. 2003; Yoshida et al. 2003, Tumlinson et al. 2004). The complexity of the feedback and the large number of unknowns (e.g. population III IMF, total ionising photon production, etc.) make this problem very challenging.

In an attempt to understand this era of primordial star cluster formation, we investigated in a previous paper (Santoro & Thomas 2003, hereafter ST03) the merger history of primordial haloes in the  $\Lambda$ CDM cosmology. There we assumed no external radiation field (other than that provided by CMB photons). The Block Model of Cole & Kaiser (1988) was used to generate the merger history of star clusters using a simple model for the collapse and cooling criterion, hence identifying those haloes that were able to form

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stars before being disrupted by mergers. We then contrasted the mass functions of all the resulting star clusters and those of primordial composition, i.e. star clusters that have not been contaminated by sub-clusters inside them. We found two generations of primordial haloes: low-temperature clusters that cool via  $H_2$ , and high-temperature clusters that cool via electronic transitions.

We investigated two regions of space each enclosing a mass of  $10^{11} h^{-1} M_\odot$ : a high-density region corresponding to a  $3\sigma$  fluctuation ( $\delta_0 = 10.98$ ), and a mean-density region ( $\delta_0 = 0$ ), where  $\delta_0$  is the initial overdensity of the root block. In the high-density region we found that approximately half of the star clusters are primordial. The fractional mass contained in the two generations was 0.109 in low temperature clusters and 0.049 in high temperature clusters. About 16 per cent of all baryons in this region of space were once part of a primordial star cluster. In the low-density case the fractional mass in the two generations was almost unchanged, but the haloes collapsed at much lower redshifts and the mass function was shifted toward higher masses.

In the present paper, as a continuation of the previous work, we include the effect of ionising radiation in two different ways: firstly we add a homogeneous background radiation field; secondly, we consider feedback from the first star clusters formed in the merger tree—these will form an ionising (and photo-dissociating) sphere around them, changing the cooling properties of neighbouring star clusters. A further improvement upon our previous work includes the use of a more realistic merger tree.

We describe our chemical network including radiative processes in Section 2, and the new merger tree method in Section 3. The effect of a global ionisation field on the formation of stars in primordial star-clusters is considered in Section 4 and that of local feedback in Section 5. Finally, we summarise our conclusions in Section 6.

## 2 PRIMORDIAL CHEMISTRY AND GAS COOLING IN THE PRESENCE OF RADIATION

### 2.1 Chemical model

In this Section we introduce the chemical network needed to follow the coupled chemical and thermal evolution under a homogeneous UV background radiation field.

The non-equilibrium chemistry code is based upon the minimal model presented in Hutchings et al. (2002, hereafter HSTC02). It calculates the evolution of the following 9 species:  $H_2$ ,  $H$ ,  $H^+$ ,  $H_2^+$ ,  $H^-$ ,  $He$ ,  $He^+$ ,  $He^{++}$  and  $e^-$ . The important cooling processes are: molecular hydrogen cooling, collisional excitation and ionisation of atomic Hydrogen, collisional excitation of  $He^+$ , and inverse Compton cooling from cosmic microwave background photons. In this paper we only consider the low density-high temperature ( $T > 300K$ ) limit. Thus, we have ignored the effects of HD cooling, which is only important in the high density-low temperature regime.

To this chemical model we have added the photo-ionisation and photo-dissociation reactions compile by Abel et al. (1997) and listed in Table 1. This consists of 9 reactions involving the interaction of each species with the

background photons. These are: photo-ionisation of  $H$ ,  $He$ ,  $He^+$  and  $H_2$ , with threshold energies of  $h\nu = 13.6, 24.6, 54.4$  and  $15.42\text{ eV}$ , respectively; photo-detachment of  $H^-$  with a threshold energy of  $0.755\text{ eV}$ , potentially an important process since  $H^-$  catalyses the formation of  $H_2$ ; and photo-dissociation of  $H_2^+$  and  $H_2$  (by the Solomon process and by direct photo-dissociation). In the case of the Solomon process dissociation happens in a very narrow energy range  $12.24\text{eV} < h\nu < 13.51\text{eV}$ .

The energy equation takes the following form:

$$\frac{d(n_t T)}{dt} = \frac{2}{3k} (\Lambda_{\text{heat}} - \Lambda_{\text{cool}}) \quad (1)$$

where  $n_t$  is the total number density of all species,  $T$  is the temperature,  $\Lambda_{\text{cool}}$  and  $\Lambda_{\text{heat}}$  are the cooling and heating terms, respectively, and we have assumed a monatomic energy budget of  $\frac{3}{2}kT$  per particle (the energy associated with rotational and vibrational states of  $H_2$  is negligible).

$$\Lambda_{\text{cool}} = \Lambda_{H,\text{ce}} + \Lambda_{H,\text{ci}} + \Lambda_{He^+,\text{ce}} + \Lambda_{H_2,\text{ce}} + \Lambda_{\text{Compton}} \quad (2)$$

where the suffixes ce and ci mean collisional excitation and ionisation respectively, and expressions for each of these terms are given in HSTC02.

$$\Lambda_{\text{heat}} = \Lambda_{H,\text{pi}} + \Lambda_{He,\text{pi}} + \Lambda_{He^+,\text{pi}} + \Lambda_{H_2,\text{pi}} + \Lambda_{H_2,\text{pd}} \quad (3)$$

where the suffixes pi and pd mean heating from photo-ionisation and photo-dissociation respectively. The expression for each term was calculated using Equation B1 from the Appendix, using the cross-sections listed in Table 1.

### 2.2 UVB spectrum

The non-equilibrium chemistry and the thermal evolution of the clouds are calculated assuming the presence of an ultraviolet radiation field of the power-law form

$$J_\nu = J_{21} \times \left( \frac{\nu}{\nu_H} \right)^{-\alpha} 10^{-21} \text{ erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}, \quad (4)$$

where  $h\nu_H = 13.6\text{ eV}$  is the Lyman limit of  $H$ . Here the direction of the radiation field is not important and the normalisation is given in terms of the equivalent isotropic field.

In the present-day Universe, QSOs have much steeper spectra ( $\alpha \approx 1.8$ , e.g. Zheng et al. 1997) than do stars ( $\alpha \approx 5$ , e.g. Barkana & Loeb 1999). However, Population III stars are likely to be biased to much higher spectral energies and their spectra may resemble those of QSOs above the Lyman limit (Tumlinson & Shull 2000; Tumlinson, Shull & Venkatesan 2003). In this paper, we take  $\alpha = 2$  which could equally well apply to either type of source.

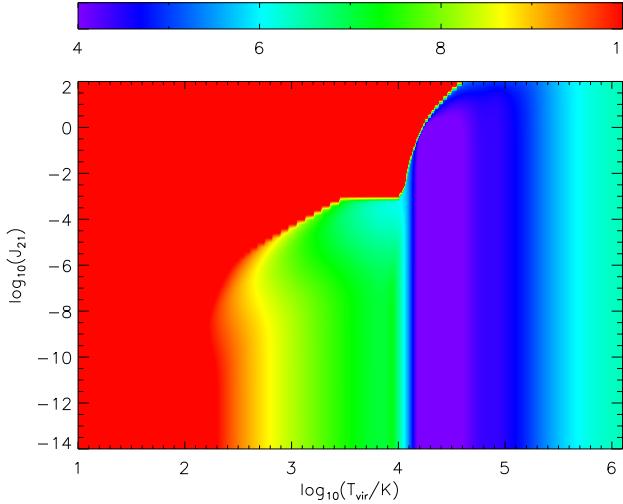
For the calculation of all the photo-ionisation and photo-dissociation rates and as well as the heating terms, we assume an optical thin medium and no self-shielding.

### 2.3 Cooling of isolated clouds

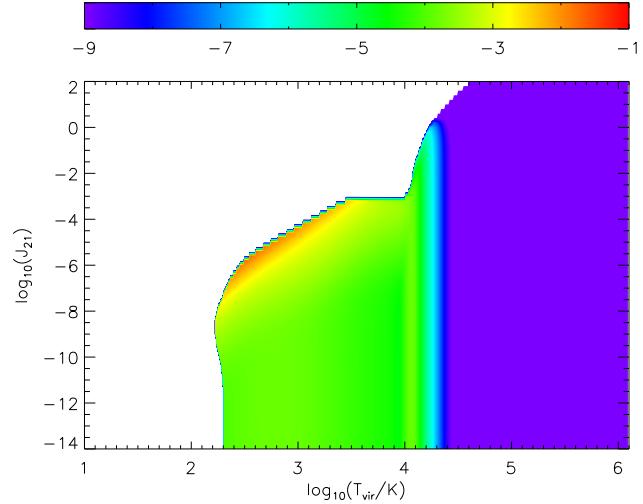
Apart from a scaling factor, the cooling time,  $t_{\text{cool}}$ , of isolated halos subject to a uniform radiation field depends solely on the ratio of the number densities of baryons,  $n_b$ , and photons,  $n_\gamma$ , i.e.  $t_{\text{cool}} = f_n(T_{\text{vir}}, n_b/n_\gamma)/n_b$ . Thus the effect of the global background radiation on single haloes can be presented in two ways: we can fix either the baryon

**Table 1.** This table summarises the important reactions that should be included in a chemical network if a uniform background radiation field is present. Compiled by Abel et al. (1997), except cross sections 25 and 27. The number index of each reaction corresponds to those in that paper. Reference: Osterbrock (1989, O89), de Jong (1972, DeJ72), O’Neil & Reinhardt (1978, OR78), Tegmark et al. (1997, TSR97), Haiman, Rees & Loeb (1996, HRL96), Abel et al. (1997, AAZN97).

Reaction	cross sections/cm <sup>2</sup>	Reference
20 $H + \gamma \rightarrow H^+ + 2e^-$	$\sigma_{20} = A_0 \left( \frac{\nu}{\nu_{th}} \right)^{-4} \left( \frac{e^{(4-4 \arctan \epsilon/\epsilon)}}{(1-e^{-2\pi/\epsilon})} \right)$ $\left\{ \begin{array}{l} A_0 = 6.30 \times 10^{-18} \text{ cm}^2 \\ \epsilon = \sqrt{\nu/\nu_{th} - 1}, \quad h\nu_{th} = 13.6 \text{ eV} \end{array} \right.$	O89
21 $He + \gamma \rightarrow He^+ + e^-$	$\sigma_{21} = 7.42 \times 10^{-18} \left( 1.66 \left( \frac{\nu}{\nu_{th}} \right)^{-2.05} - 0.66 \left( \frac{\nu}{\nu_{th}} \right)^{-3.05} \right)$ , $\nu > \nu_{th}$	O89
22 $He^+ + \gamma \rightarrow He^{++} + e^-$	$\sigma_{22} = (A_0/Z^2) \left( \frac{\nu}{\nu_{th}} \right)^{-4} \left( \frac{e^{(4-4 \arctan \epsilon/\epsilon)}}{(1-e^{-2\pi/\epsilon})} \right)$ , $h\nu_{th} = Z^2 \times 13.6 \text{ eV}$ and $Z = 2$ .	O89
23 $H^- + \gamma \rightarrow H + e^-$	$\sigma_{23} = 7.928 \times 10^5 (\nu - \nu_{th})^{\frac{3}{2}} \left( \frac{1}{\nu^3} \right)$ , $h\nu > h\nu_{th} = 0.755 \text{ eV}$	DeJ72
24 $H_2 + \gamma \rightarrow H_2^+ + e^-$	$\sigma_{24} = \begin{cases} 0 & : h\nu < 15.42 \text{ eV} \\ 6.2 \times 10^{-18} h\nu - 9.40 \times 10^{-17} & : 15.42 < h\nu < 16.50 \text{ eV} \\ 1.4 \times 10^{-18} h\nu - 1.48 \times 10^{-17} & : 16.5 < h\nu < 17.7 \text{ eV} \\ 2.5 \times 10^{-14} (h\nu)^{-2.71} & : h\nu > 17.7 \text{ eV} \end{cases}$	OR78
25 $H_2^+ + \gamma \rightarrow H + H^+$	$\sigma_{25} = 7.401 \times 10^{-18} 10^{(-x^2 - 0.0302x^3 - 0.0158x^4)}$ $\left\{ \begin{array}{l} x = 2.762 \ln(h\nu/11.05 \text{ eV}) \\ h\nu > 2.65 \text{ eV} \end{array} \right.$	TSR97
26 $H_2^+ + \gamma \rightarrow 2H^+ + e^-$	$\sigma_{26} = 10^{-16.926 - 4.528 \times 10^{-2} h\nu + 2.238 \times 10^{-4} (h\nu)^2 + 4.245 \times 10^{-7} (h\nu)^3}$ , $30 \text{ eV} < h\nu < 90 \text{ eV}$	AAZN97
27 $H_2 + \gamma \rightarrow H_2^* \rightarrow H + H$	$\sigma_{27} = 3.71 \times 10^{-18}$ , $12.24 \text{ eV} < h\nu < 13.51 \text{ eV}$	HRL96
28 $H_2 + \gamma \rightarrow H + H$	see Reference for the expression	AAZN97



**Figure 1.** The cooling time,  $t_{\text{cool}}$  in the  $J_{21} - T_{\text{vir}}$  plane. The colour bar is  $\log_{10}(t_{\text{cool}}/\text{yr})$ . This plot was calculated at a fixed density corresponding to  $z = 20$ .



**Figure 2.** The molecular hydrogen fraction,  $f_{H_2}$ , after one cooling time, in the  $J_{21} - T_{\text{vir}}$  plane. The region corresponding to clouds that have not cooled by the time the expansion factor reaches 10 has been coloured white.

density or the amplitude of the radiation field and vary the other.

Figure 1 shows the cooling time,  $t_{\text{cool}}$ , of haloes exposed to different levels of background radiation for a fixed density of  $n_H \approx 0.31 \text{ cm}^{-3}$ , corresponding to the mean density within a collapsed halo at  $z = 20$ , as seen from the  $J_{21} - T_{\text{vir}}$  plane.  $t_{\text{cool}}$  is defined as the time that the halo takes to cool from virialisation to the moment when  $T = 0.75T_{\text{vir}}$  (or, if it doesn’t cool, we stop the integration when the scale factor reaches 10). Any halo that falls on the red region will not be able to cool in a Hubble time. On the

other hand haloes on the dark blue or violet part of the plot will cool in much less than a dynamical time.

In Figure 2 we show the fractional density of molecular hydrogen,  $f_{H_2}$ , after one cooling time in the  $J_{21} - T_{\text{vir}}$  plane. The region that has not cooled by the time the scale factor reaches 10 has been coloured white. For the zero-flux case, we see that the highest molecular fractions occur for a virial temperature of just over  $10^4 \text{ K}$ . Halos of this temperature are able to partially ionize hydrogen atoms and the free electrons then go on to catalyse production of  $H_2$ .

From these plots, we can see that the ionising radiation

has two main effects. Firstly, it provides a heat source that prevents cooling of halos. The minimum virial temperature of halos that can cool gradually increases along with the photon flux, whereas the heating has little effect on halos above this temperature. The effect is visible in Figure 1 as a sharp transition between the green/blue and red regions that runs diagonally across the plot.

Secondly, the ionizing flux can boost cooling of low-temperature halos ( $T_{\text{vir}} \leq 10^4$  K) by creating free electrons that then catalyse the production of H<sub>2</sub>. For any given temperature, there is only a narrow range of photon fluxes for which this is important before photo-heating swamps the increased H<sub>2</sub> cooling.

Thus, as the background ionising radiation builds up in the Universe, we expect there at first to be a small boost in the formation of low-temperature (low-mass) star clusters and then a sharp decline. The precise values of  $J_{21}$  at which this occurs will depend upon the redshift of structure formation (recall that the above plots are for a redshift of 20 and the required values of  $J_{21}$  will scale as  $(1+z)^3$ ). In Section 4 we consider both specific values of  $J_{21} = 10^{-10}, 10^{-5}, 10^{-2}$  & 10 and also a time-evolving ionisation field.

### 3 MERGER TREE

In a previous paper (Santoro & Thomas 2003) we generated merger histories of dark matter halos using the block model of Cole & Kaiser (1988). In this model, a parent block of mass  $M_0$  and density fluctuation  $\delta_0$  is halved producing two daughter blocks of mass  $M_1 = M_0/2$ . Extra power, drawn at random from a Gaussian distribution, is then added to one block and subtracted from the other in order to conserve the overall level of fluctuations in the root block. This process is then repeated until the desired resolution has been reached. The reader should note that the tree is produced by stepping back in time. Therefore, the formation of the daughter blocks occurs at a higher redshift than their parent block. A valid criticism of this model is that the mass distribution is not smooth, as each level changes in mass by a factor of two. This discretisation of mass is an undesirable constraint on our model and for this reason we have moved to a more realistic method of generating the merger tree.

We now use a Monte-Carlo algorithm to generate the merger tree. There are a number of codes which use this technique (e.g. Kauffmann & White 1993; Somerville & Kolatt 1999) however, we have chosen the method proposed by Cole et al. (2000). In short, the code uses the extended Press-Schechter formalism to generate the merger histories of dark matter halos, but we refer the reader to this paper for a complete discussion of the code. The main advantage of this method over the block model is that the discretisation of mass has been removed.

Unlike most previous tree implementations, we do not place our merger tree onto a predefined grid of timesteps but utilise a very fine time resolution. This allows us to retain the block model's prescription of two progenitors per merger, consistent with our previous work. The algorithm allows us to account for the accretion of mass below the resolution limit, however we assume that this will not seriously affect the structure and cooling of the halo.

An important aspect of the code is how we treat the mergers of halos. The outcome of a merger will depend upon the ratio of masses of the merging halos,

$$q = \frac{M_1}{M_2}, \quad (5)$$

where  $M_1 < M_2$ . Consequently, we introduce,  $q_{\text{min}}$ , as the minimum mass ratio to affect the cooling of a halo. This leads to two cases:

- If  $q > q_{\text{min}}$  then the two halos merge and their cooling is completely disrupted. The gas is then shock heated to the virial temperature of the parent halo, erasing all previous cooling information, and the cooling starts afresh.
- If  $q < q_{\text{min}}$  then we assume that the smaller of the two daughters is disrupted. We then compare the times at which the larger daughter and the parent halo would cool. If the former occurs first then we postpone the merger and allow the cooling of the daughter to proceed; otherwise we continue as for  $q > q_{\text{min}}$ .

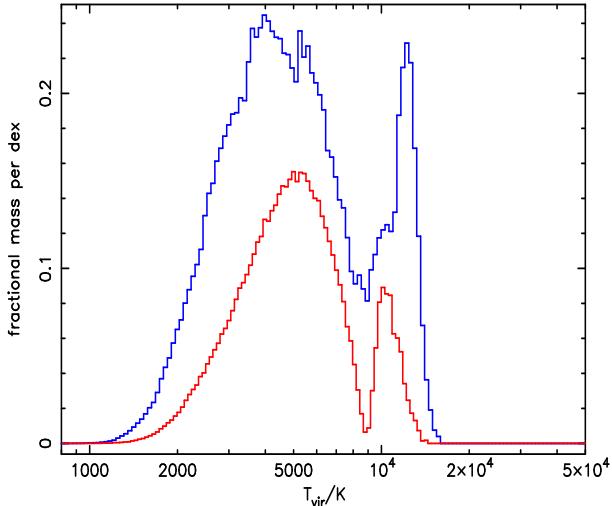
In the future we would like to determine an appropriate value for  $q_{\text{min}}$  from hydrodynamical simulations. Simulations of galaxy mergers (e.g. Mihos & Hernquist 1996) show that when objects with mass ratios  $q > 0$ . collide the galactic structure of both objects is seriously disrupted. They classify these as 'major' mergers. We suspect that smaller mass ratios would still sufficiently disrupt the cooling gas cloud. Consequently, for this work we set  $q_{\text{min}} = 0.25$ . Although we do not show it here, our results remain largely unchanged in the range  $0.2 < q_{\text{min}} < 0.3$ .

We treat the metal enrichment of halos in the same way as ST03 where it was assumed that, regardless of whether or not star clusters survive a merger, they instantly contaminate their surroundings with metals and the enrichment is confined to the next level of the merger hierarchy (i.e. the metals do not propagate into halos on other branches). This is the same for both the global (section 4) and local models (section 5).

Once a halo has been contaminated it is no longer classed as primordial, irrespective of whether it can form more stars or not. However, no attempt is made to account for the transition from population III to population II star-formation. Consequently, contaminated halos are assumed to cool at the same rate as their primordial counterparts and in the case of our local model, produce the same ionising flux. We intend to investigate the effect of this transition in future work by including cooling from metals.

In this paper, in common with ST03, we use a root mass of  $10^{11} M_{\odot}$  for our tree, and a mass resolution of  $9.5 \times 10^4 M_{\odot}$ . However, we use slightly different cosmological parameters as derived from the WMAP data (Spergel et al. 2003) of  $\Omega_0 = 0.3$ ,  $\lambda_0 = 0.7$ ,  $\Omega_{b0} = 0.0457$ ,  $h = 0.71$ ,  $\sigma_8 = 0.9$ , and a power spectrum as calculated by CMBFAST.

Figure 3 shows a comparison between the new merger tree (red line) and the older Block Model from ST03 (blue line) of the fractional mass per dex of primordial star clusters as a function of virial temperature, averaged over a large number of realisations and in the absence of ionising radiation. It is clear that the new tree has had a significant affect on the number of primordial objects that are formed. While the total number of objects that are able to cool remains roughly constant, our new model produces only a third of



**Figure 3.** The fractional mass per dex of primordial star clusters as a function of virial temperature: red line – new merger tree, blue line – Block Model.

the primordial objects compared with the original, although the mass fraction has only been reduced by half. Qualitatively the results remain unchanged: we still observe two generations of halos, distinguished by their primary cooling mechanism, as discussed in ST03. In addition, we have removed all features associated with the discrete mass steps (e.g. the feature at  $\sim 5000$  K in the original model).

The smoothed mass distribution has lead to many unequal mass mergers which were not present in the previous model thus increasing the likelihood of contaminating large haloes with much smaller ones which happen to cool first. Equally, the chance that haloes are involved in mergers that disrupt their cooling is increased. These effects conspire to reduce the overall number of primordial objects.

## 4 GLOBAL IONISATION FIELD

### 4.1 Model

In this section, we consider the effect of a global ionisation field that affects all halos equally. As previously mentioned, we will restrict ourselves to a power law ionising flux with index  $\alpha = 2$ , corresponding either to a quasar spectrum or that of stars of primordial composition. We present results for four cases of constant normalisation:  $J_{21} = 10^{-10}, 10^{-5}, 10^{-2}$  & 10. These are chosen to be representative of a very low flux where the effect on each halo is minimal; a flux which has a positive effect on the capacity of the gas to form  $H_2$ ; and two examples of higher amplitude fluxes that destroy  $H_2$ .

In addition to the cases outlined above, we consider a time-dependent build up of the background flux. Using radiative hydrodynamical calculations to examine the effect of the UV background on the collapse of pre-galactic clouds, Kitayama et al. (2000) modelled the evolution of a UV background as:

$$J_{21}(z) = \begin{cases} e^{-\beta(z-5)} & : 5 \leq z \leq z_{\text{uv}} \\ 1 & : 3 \leq z \leq 5 \\ \left(\frac{1+z}{4}\right)^4 & : 0 \leq z \leq 3. \end{cases}$$

We adopt their model and fiducially fix the onset of the UV background at  $z_{\text{uv}} = 50$  (at which time the normalisation is negligible). We have added a factor of  $\beta$  into this expression so as to control the rate at which the field builds up and present results for 3 cases:  $\beta = 0.8$  (rapid), 1 (standard), and 2 (slow).

For the latter cases especially, the global ionising flux can be thought of as coming from pre-existing star clusters (or quasars) that form in high-density regions of space and that are gradually ionising the Universe around them. For this reason, we take the mean-density of the tree to be equal to that of the background Universe. In Section 5, we will consider a high-density region for which the ionisation field is generated internally from the star clusters that form in the tree.

### 4.2 Results

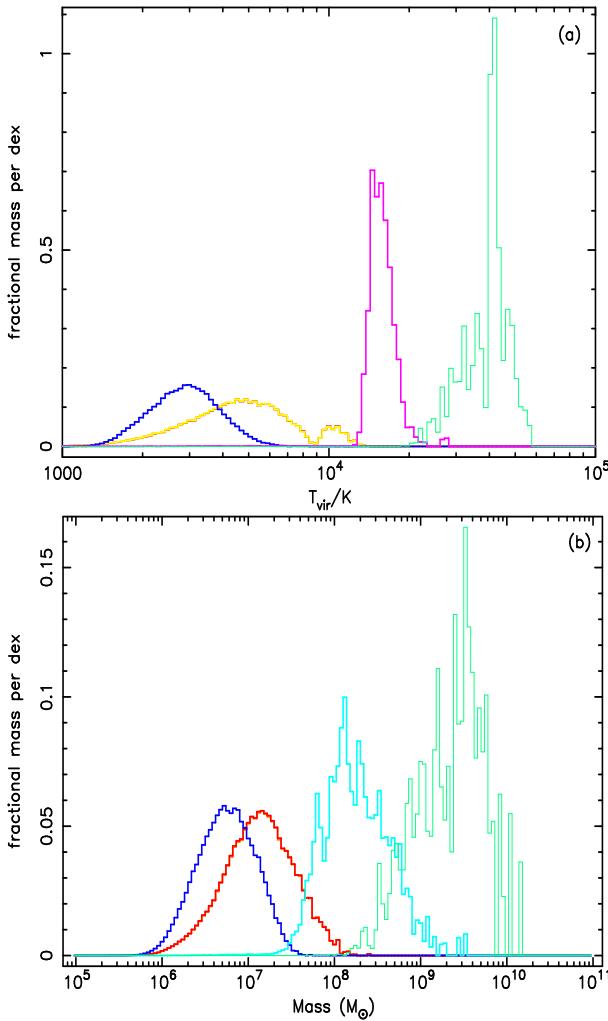
In Figure 4 we plot the fractional mass of primordial star clusters as a function of (a) virial temperature and (b) halo mass. The colours red, blue, cyan & green correspond to  $J_{21} = 10^{-10}, 10^{-5}, 10^{-2}$  & 10, respectively—note that the peak of the distributions do *not* move steadily from left to right as  $J_{21}$  is increased. Figure 5 shows histograms of the star-formation redshifts of the primordial clusters.

The lowest amplitude case is almost indistinguishable from that of zero flux. For this reason we have not plotted the latter. There are two bumps in the virial temperature histogram corresponding to two distinct cooling mechanisms. In ST03, these were christened Generation 1 (low-virial temperature,  $T \leq 8600$  K, low-mass, high collapse redshift, dominated by  $H_2$  cooling) and Generation 2 (high-virial temperature,  $T \geq 8600$  K, high-mass, low collapse redshift, dominated by electronic cooling).

As the flux is increased, the effect of the radiation field is to promote the cooling of Generation 1 halos. The typical virial temperature and mass of such halos decreases, and the number of Generation 2 star clusters is reduced as collapsing halos are more likely to have been polluted by metals from smaller objects within them. For  $J_{21} = 10^{-5}$  (blue curve), the effect is so pronounced that it completely eliminates Generation 2 objects. However this is an extreme case, because, as Figures 1 & 2 show, this flux has been chosen to produce close to the maximum possible enhancement in the  $H_2$  fraction and a corresponding reduction in cooling time throughout the redshifts at which these halos form.

If the background flux is increased further, then the enhancement in Generation 1 star clusters is reversed. For  $J_{21} = 10^{-2}$  (cyan curve) the balance has shifted almost entirely in the favour of Generation 2 clusters and by  $J_{21} = 10$  all Generation 1 clusters have been eradicated.

It is interesting to note that the mass fraction of stars contained in primordial star clusters is not greatly affected by the normalisation of the ionising radiation, varying from 0.05 to 0.1. However, the mass (and hence number) of the star clusters varies substantially. A modest flux will increase the number of small clusters, moving the mass function to



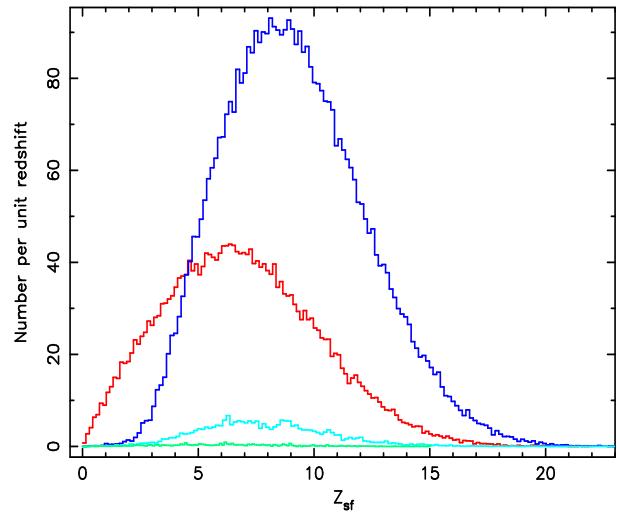
**Figure 4.** Fractional mass per dex of primordial objects as a function of (a) virial temperature and (b) mass, for 4 different cases: red corresponds to  $J_{21} = 10^{-10}$ ; blue to  $J_{21} = 10^{-5}$ ; cyan to  $J_{21} = 10^{-2}$ ; and green to  $J_{21} = 10$ .

lower masses while a greater flux produces the opposite effect.

The number of primordial star clusters as a function of star formation redshift is shown in figure 5. The redshift distribution is similar in all cases, which differs significantly from model with time-varying flux, discussed next.

Figure 6 plots the fractional mass of primordial star clusters, as a function of (a) virial temperature and (b) mass. Unlike our previous results, the introduction of a time-evolving field has had a devastating effect on the mass fraction of primordial objects. As the rate at which the flux builds-up increases, the peak of the Generation 1 mass function moves towards lower masses (and virial temperatures) and its normalisation decreases significantly. At the same time, as shown in figure 7, the peak in the production rate moves to higher redshifts. In each case, it corresponds to a flux of  $J_{21} \approx 5 \times 10^{-5}$  for which, from the previous results, an enhancement in the  $H_2$  fraction and hence a decrease in the cooling time is expected.

The effect on the production of higher-mass, higher-



**Figure 5.** Histograms of star-formation redshifts for primordial halos. The colour coding is the same as in Figure 4.

virial-temperature star clusters, is more complicated. In this paper we are concerned with primordial objects, by which we mean those with zero metallicity. The key question, then, is whether large halos are contaminated by metals from sub-clusters within them. With a slow build-up of flux cooling in these sub-clusters is enhanced resulting in increased contamination and a reduction in the number density of primordial Generation 2 halos. However, a rapid build-up of flux cuts off production of small halos dramatically and the number of primordial Generation 2 halos is increased.

## 5 LOCAL FEEDBACK

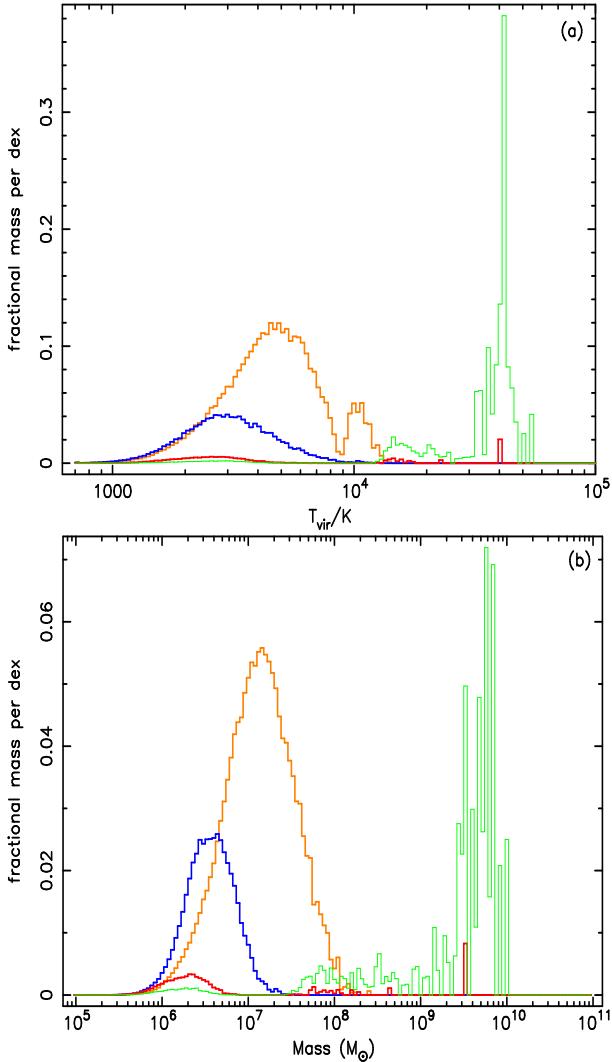
In this section, we consider local feedback, i.e. that produced by star clusters internal to the tree.

### 5.1 Model

#### 5.1.1 Physical picture and assumptions

The large value of the Thomson electron-scattering optical depth in the WMAP data of  $\tau = 0.17 \pm 0.04$  (Spergel et al. 2003) suggests an early reionisation era at  $11 < z < 30$  ( $180^{+220}_{-80}$  Myr after the Big Bang). This requires a high efficiency of ionising photon production in the first stars, corresponding to a deficit of low-mass stars. This is backed up by theoretical arguments and simulations (e.g. Abel et al. 2002; Bromm et al. 2002; Schaerer 2002; Tumlinson et al. 2004; Santoro & Shull 2005) of star-formation in a primordial gas, for which fragmentation was found to be strongly inhibited by inefficient cooling at metallicities below about  $10^{-3.5} Z_\odot$ .

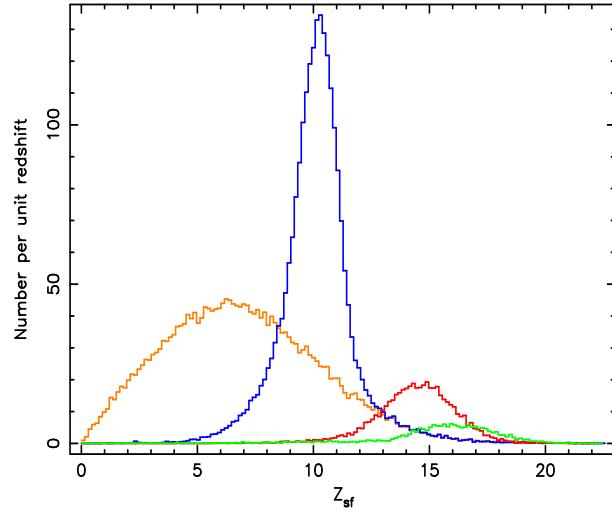
There is still some debate as to whether the first star forming halos will produce a single massive star (e.g. Abel et al. 2002) or fragment further to form the first star clusters (e.g. Bromm et al. 1999). Whichever of these is correct makes little difference to our results. Tumlinson et al. (2004) considered a number of IMFs that may lead to the required early reionisation. These have



**Figure 6.** Fractional mass per dex of primordial objects as a function of (a) virial temperature and (b) mass, for 4 different cases: orange corresponds to the no flux case; blue to  $\beta = 2$ ; red to  $\beta = 1$ ; and green to  $\beta = 0.8$ .

ionising fluxes per unit mass in the range  $Q \approx 10^{47} - 10^{48} \text{ ph s}^{-1} \text{ M}_\odot^{-1}$ , but they all have similar ionising efficiencies of about 80 000 photons/baryon when integrated over the whole life of the stars. A value which is similar to that obtained for single massive stars ( $M \gtrsim 20 \text{ M}_\odot$ ). If we assume a uniform flux over time, then this corresponds to mean lifetimes of  $3.0 \times 10^7 - 3.0 \times 10^6$  yr, respectively. Note that these values of  $Q$  are much greater than the average for the Milky Way,  $Q \approx 8.75 \times 10^{43} \text{ ph s}^{-1} \text{ M}_\odot^{-1}$  (Ricotti & Shull 2000).

When halos in the merger tree are able to cool, we assume that they will convert part of their baryonic component into a “star cluster” (primordial or otherwise). These objects will exert radiative feedback onto the next generation of haloes that form inside the same tree. The photon flux will also depend upon the star-formation efficiency and the escape fraction from the star-forming region in the centre of the halo. In this paper, we are not concerned with the



**Figure 7.** Histograms of star-formation redshifts for primordial halos. The colour coding is the same as in Figure 6.

**Table 2.** Parameters of the ionisation models that we consider: model number; fraction of mass in stars,  $f_*$ ; specific ionising fluxes,  $Q_0$ , in units of  $\text{ph s}^{-1} \text{ M}_\odot^{-1}$ ; total number of ionising photons,  $N_0$ , and ionising flux,  $S_0$ , in units of  $\text{ph s}^{-1}$  per solar mass of matter (baryonic plus dark); and the time for which the ionising flux acts,  $t_*$ , in units of years.

id	$f_*$	$Q_0$	$N_0$	$S_0$	$t_*$
1 (red)	$10^{-2}$	$10^{48}$	$1.5 \times 10^{59}$	$1.5 \times 10^{45}$	$3 \times 10^6$
2 (green)	$10^{-3}$	$10^{48}$	$1.5 \times 10^{58}$	$1.5 \times 10^{44}$	$3 \times 10^6$
3 (blue)	$10^{-3}$	$10^{47}$	$1.5 \times 10^{58}$	$1.5 \times 10^{43}$	$3 \times 10^7$

magnitude of metal production and so it is only the combination of the two,  $f_*$ , that is of interest.

The total ionising flux from a halo is

$$S = f_* M_b Q, \quad (6)$$

where  $M_b \approx 0.152 M$  is the baryonic mass and  $M$  is the total mass of the halo. We will present results for 3 models, listed in table 2. Model 1 has the highest ionising flux; model 2 has a smaller flux but lasts for the same length of time; model 3 has an even smaller flux but lasts for longer so that the total number of ionising photons produced is the same as for model 2.

Once the stars have formed, the ionising photons will begin to evaporate the rest of the halo and make their way into the surrounding IGM. Each star cluster produces

$$N_\gamma = 80 000 \frac{f_* M_b}{m_H} \quad (7)$$

ionising photons, where  $M_b$  is the baryonic mass. In the absence of recombination, this is sufficient to ionise the hydrogen in a region of baryonic mass

$$M_{b\gamma} = N_\gamma \mu_H m_H, \quad (8)$$

where  $\mu_H \approx 1.36$  is the mean molecular mass per hydrogen nucleus. For the star-formation efficiencies and top-heavy initial-mass function that we consider here, there are more

than enough photons to ionise any neutral gas within the star-cluster:

$$\frac{M_{b\gamma}}{M_b} = 80000 f_* \mu_H \approx 1.1 \times 10^5 f_*. \quad (9)$$

We next consider whether it is correct to neglect recombinations. The photon flux required to maintain ionisation of the halo (at the mean halo density) is given by

$$S_{\text{halo}} = \frac{4\pi}{3} R^3 n_H^2 \mathcal{R}, \quad (10)$$

where  $R$  is the radius of the virialised halo,  $n_H$  is the combined number density of all species of hydrogen, and  $\mathcal{R}$  is the recombination rate (see, e.g. Hutchings et al. 2002). The value of  $S_{\text{halo}}$  would be higher if we were to take into account clumping of the gas. On the other hand, there are two effects that will tend to lower  $S_{\text{halo}}$ : for high-temperature halos not all the gas will be neutral; for low-temperature halos the gas will be raised to a temperature that exceeds the virial temperature and so will tend to escape from the halo—the sound-crossing time for a gas at  $10^4$  K is of order  $1.0 \times 10^7$  yr for a  $10^6 M_\odot$  halo at an expansion factor  $a = 0.05$ . We assume that these effects will roughly cancel and set the nett photon flux that escapes the halo equal to  $S_{\text{esc}} = S - S_{\text{halo}} = f_{\text{esc}} S$ . Here

$$1 - f_{\text{esc}} = \frac{S_{\text{halo}}}{S} \approx 0.12 \left( \frac{a}{0.05} \right)^{-3} \left( \frac{S_0}{1.5 \times 10^{44} \text{ ph s}^{-1}} \right)^{-1}, \quad (11)$$

where we have set  $\mathcal{R}$  equal to the recombination rate for a  $10^4$  K gas. Of course,  $f_{\text{esc}}$  is not allowed to drop below zero. The number of ionising photons that escape the source halo is

$$N_{b\gamma, \text{esc}} = f_{\text{esc}} N_{b\gamma}. \quad (12)$$

Escaping photons are now free to propagate into the inter-halo medium (aka inter-galactic medium or IGM) and irradiate nearby halos. At the mean density of the IGM, the Strömgren radii for any ionised regions are very large, and only model 1 produces enough photons to ionise out to the Strömgren radius, and then only at very early times,  $a \lesssim 0.02$ . A better picture is that of a bubble of ionised gas whose outer radius grows with time until the ionising source switches off. To a good approximation then, and for simplicity, we assume that recombinations in the IGM are negligible.

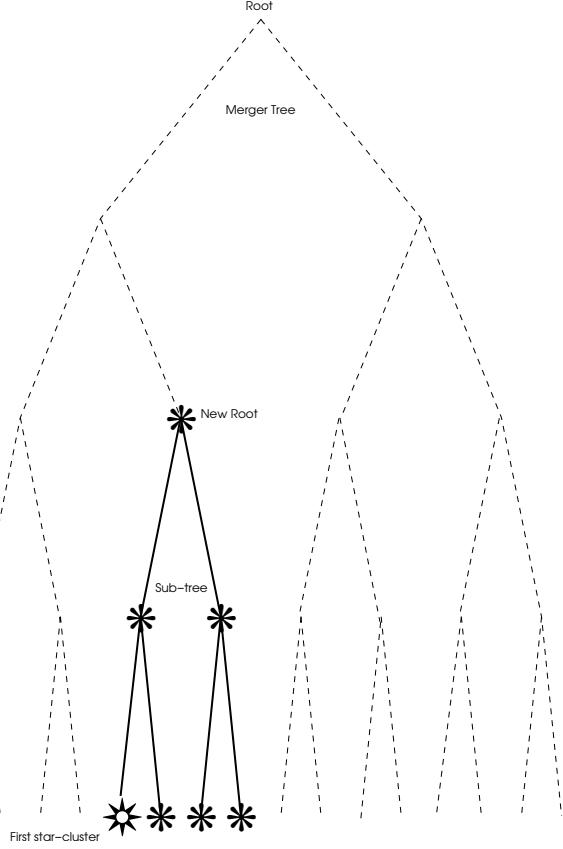
### 5.1.2 Numerical methodology

The local feedback is implemented as follows. First the tree is scanned for all star clusters and a list is generated, in order of decreasing star formation redshift. Starting with the first cluster, we work up the tree looking at the baryonic mass of successive parent halos,  $M_{b,\text{par}}$  until the last halo for which

$$M_{b,\text{par}} < M_b + M_{b\gamma, \text{esc}}. \quad (13)$$

The sub-tree below this parent halo (see Figure 8) defines the extent of the ionised region and the cooling times of all halos within it are recalculated taking into account the amplitude of the flux and the time for which it acts.

The tree provides limited information about the spatial distribution of halos. However, we know that halos are confined within a common parent halo and that the parent will



**Figure 8.** Schematic view of the merger tree under internal feedback. Once the first star cluster is located, the code calculates how many levels up the tree has to go to re-calculate the cooling times of each halo under the new root, this time under the influence of the radiative flux coming from that first star cluster. In this example, the feedback region reaches two levels up the tree. Then, the whole sub-tree cooling times will be re-evaluated.

not have collapsed at this time. So we take the separation of the star cluster and each neighbouring halo to be equal to the radius of a sphere at the mean density at that time that encloses a mass equal to that of the first common parent:

$$R_{\text{par}} = a \left( \frac{3 M_{b,\text{par}}}{4\pi \Omega_{b0} \rho_{c0}} \right)^{1/3} \quad (14)$$

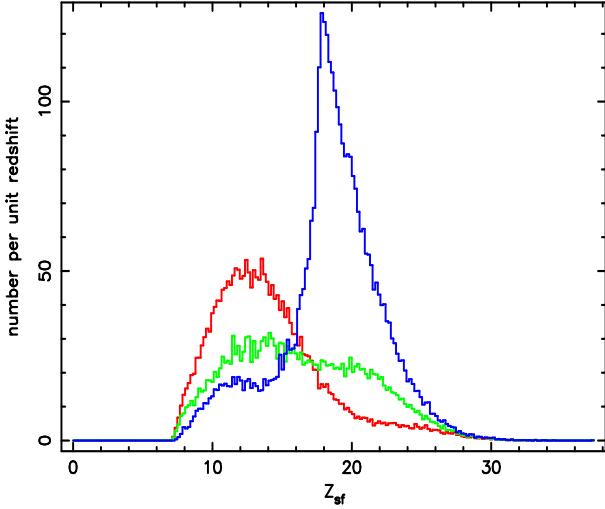
where  $a$  is the scale factor at the time of star formation and the other quantities have the usual meanings. Note that the value of  $M_{b,\text{par}}$  in equation 14 will vary depending upon how far one has to travel up the tree to find a common neighbour.

The flux density,  $F$ , at a distance  $R_{\text{par}}$  from the source is given by:

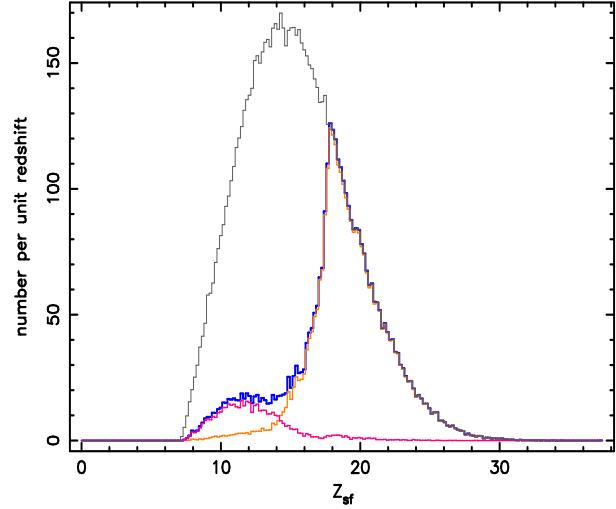
$$F = \frac{S_{\text{esc}}}{4\pi R_{\text{par}}^2} \quad (15)$$

We need to convert this into an equivalent value of  $J_{21}$  for input into our chemical evolution code. To do this we integrate the spectrum given in equation 4 over all frequencies and angles

$$F = 4\pi \int_{\nu_H}^{\infty} \frac{J_\nu}{h\nu} d\nu = \frac{4\pi}{\alpha} J_{21}, \quad (16)$$



**Figure 9.** Histograms of the star formation redshifts of primordial star clusters averaged over a large number of realisations. The colours correspond to different models of local feedback as listed in table 2.



**Figure 10.** Histogram of star-formation redshifts for primordial haloes. Here we compare model 3 (blue) with the the no flux case (grey). Also show are the contributions from Generation 1 (orange) and Generation 2 (magenta) halos.

where  $h\nu_H = 13.6\text{eV}$  is the energy of H ionisation. Combining these two equations allows us to express the ionising flux as an equivalent value of  $J_{21}$  for an isotropic radiation field (the directionality of the radiation field is unimportant in this context). We use the value of  $J_{21}$  and duration of the ionisation as inputs to the chemistry code to obtain the new cooling time of each neighbouring halo in the sub-tree, using the heating and cooling processes explained in Section 2.3.

The list of remaining clusters is then re-ordered using the new star-formation redshifts and we continue with the next halo in the list. The process is repeated until we reach the bottom of the list or until the next halo in the list is not able to cool in a Hubble time.

## 5.2 Results

The first stars are widely predicted to form in high density regions of space. Consequently, in this section we present results of simulations with internal radiative feedback in a region for which the root halo corresponds to a positive  $3\sigma$  density fluctuation.

Figure 9 plots histograms of star formation redshifts for primordial halos for the three cases shown in Table 2, averaged over a large number of realisations. It is evident that the redshift evolution is markedly different for the three curves and we shall discuss each in turn.

First of all, in figure 10, we compare model 3 with the case of zero flux. We can clearly see that the evolution of the two curves is identical up to a point, after which model 3 drops away dramatically. This sudden change can be understood by examining equation 11. We are interested in the redshift at which the ionising photons first begin to escape the halo. If we set  $f_{\text{esc}}$  equal to zero and solve for the scale factor,  $a$ , we find that, for this particular model, photons do not break out until a redshift  $z \sim 18$ , in agreement with what is seen in figure 10. Also shown are the contributions from the two different halo generations, discussed in previous

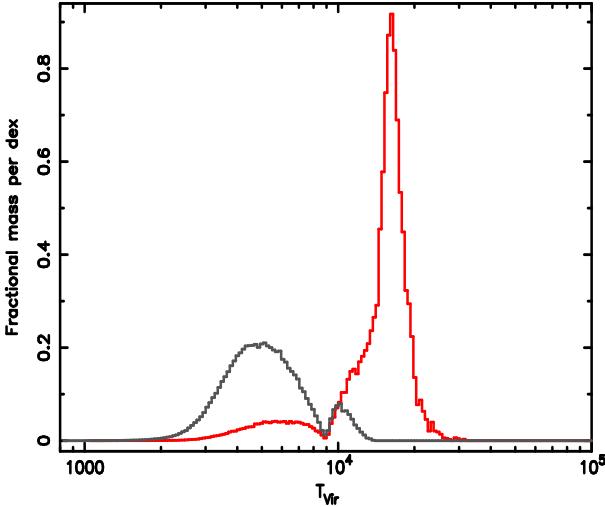
sections. The escaping photons have had a devastating impact on the surrounding halos, particularly the smaller, Generation 1 halos. As a result there is a rise in the number of Generation 2 halos because the reduced contamination at early times allows more massive halos to cool as primordial objects.

In models 1 & 2 the photons are able to escape the halo at much earlier times (before any objects have been able to cool). As such, the first primordial objects to form will immediately begin to influence their surroundings. This explains the much greater reduction in Generation 1 star clusters for these models compared to model 3, seen in figure 9.

Figure 11 plots the fractional mass per dex of primordial objects as a function of temperature for our highest flux case (model 1). As expected, the higher flux has suppressed the the small, low temperature halos at high redshift, thus reducing the amount of early contamination. Once again we see that there has been an enhancement in the number of high temperature, high mass halos, the distribution of which is reminiscent of that seen in figure 4 for the high values of  $J_{21}$  in our global model, particularly  $J_{21} = 10^{-2}$ . Indeed, the average  $J_{21}$  values received by halos in this model are in the range  $J_{21} = 10^{-3} - 10^{-2}$ , consistent with our previous results.

With ten times fewer photons, we expect model 2 to be less destructive than model 1 at higher redshifts and figure 9 confirms this fact. The green curve shows more primordial objects early on which consequently reduces the number of Generation 2 objects that form. Interestingly, this model shows an approximate balance between the two generations with a roughly constant formation rate of primordial halos between redshifts  $z \sim 10 - 22$ .

The mass fraction of stars contained in primordial star clusters for all the models presented here remains relatively constant, varying from 0.06 to 0.13. However, the mass functions vary substantially as do the star formation histories.



**Figure 11.** Fractional mass per dex of primordial objects as a function of temperature, for model 1 (red) and the no flux case (grey).

As the specific ionizing flux increases, the balance moves towards later star formation and more Generation 2 primordial star clusters. The positive feedback into Generation 1 clusters seen in figure 4 for intermediate values of  $J_{21}$  lasts for too short a time to be noticeable.

## 6 DISCUSSION

This paper looks at the impact of radiative feedback on primordial structure formation. This is done in two ways.

The first part investigates the properties of primordial objects under a global UV background. The merger tree is illuminated by a constant and isotropic radiation field of four different intensities, parametrised by a constant value of  $J_{21}$ :  $10^{-10}$ ,  $10^{-5}$ ,  $10^{-2}$  and 10. It seems more plausible that any background radiation field would gradually build up over time with the formation of more and more primordial stars. Consequently, we also investigate a time-dependent build-up of the background flux using an extension of the model of Kitayama et al. (2000). The section of the paper uses a mean-density region of space as the background radiation field is assumed to come from external sources within higher-density regions.

The effect of a constant UV field on the halo population is not a trivial one as both positive or negative feedback can arise from different choices of the flux amplitude  $J_{21}$ . The cooling of a low-temperature primordial gas is almost completely dominated by the release of energy from roto-vibrational line excitation of  $\text{H}_2$ . But if a radiation field is present,  $\text{H}_2$  is easily destroyed by Lyman-Werner photons ( $11.2\text{eV} < h\nu < 13.6\text{eV}$ ). On the other hand, the formation of  $\text{H}_2$  can be enhanced by an increase in the ionization fraction produced by a weak ionising flux, as electrons act as a catalyst for the formation path of  $\text{H}_2$ . At modest flux levels of  $J_{21} \sim 10^{-5}$  the nett effect is to boost cooling in the first star clusters. A similar result has previously been found by

Haiman et al. (1996), Ricotti et al. (2001), Kitayama et al. (2001) and Yoshida et al. (2003).

Negative feedback is produced not only by photo-dissociation of  $\text{H}_2$ ; at high flux levels the dominant effect comes from heating associated with photo-ionisation of H. For fluxes of  $J_{21} \geq 10^{-2}$  we find that molecular cooling is ineffective and only haloes with virial temperatures of  $T_{\text{vir}} > 14000\text{K}$  are able to cool in a Hubble time. Because of reduced contamination from star-formation in low-mass halos, strong radiation fields can increase the number of high-mass primordial star clusters.

The second part of this paper dealt with a model in which the radiative feedback is localised. That is, star clusters irradiate their surrounding area, changing the cooling properties of those primordial objects that are inside their ionisation spheres. For this model we considered only a high density region corresponding to a  $3\sigma$  fluctuation since the first objects are thought to form in regions of high over-density.

The effect of the feedback depends mainly upon the specific ionising flux, averaged over the mass of the halo. When this is low, most or all of the photons will be used up in maintaining the ionisation of the halo. For the particular model that we describe in this paper, equation 11 relates the escape fraction,  $f_{\text{esc}}$ , of ionising photons to the specific ionising flux,  $S_0$ , and redshift. A value of  $S_0$  below  $10^{43}\text{ph s}^{-1}\text{M}_{\odot}^{-1}$  will reduce  $f_{\text{esc}}$  to zero until the redshift drops to about 16, corresponding to the peak in the production rate of primordial halos per unit redshift. Although the precise number will be model dependent, we regard this as a fiducial value below which feedback will be ineffective.

Higher values of  $S_0$  result in shift from primordial star clusters away from Generation 1 (low virial temperature) towards Generation 2 (high virial temperature). Unlike the case of a global ionisation field, Generation 1 clusters are not eradicated completely, because some must form in order to provide the feedback. However, a specific ionisation flux of  $S_0 = 10^{45}\text{ ph s}^{-1}\text{M}_{\odot}^{-1}$  is enough to swing the balance strongly in favour of Generation 2 star clusters.

This paper makes a number of advances on our previous modelling, most notably the use of an improved merger tree that does not restrict halos to factors of two in mass, and the introduction of a radiation field. The former results in a reduced mass fraction of stars in primordial halos with the bias shifting more in favour of Generation 1; however, the latter moves the bias back the other way. The conclusions of HSTC02 and ST03 remain valid in that there could be a substantial population of primordial star clusters that form in high-mass halos dominated via electronic cooling.

Further improvements to our model are possible. Although we do not expect these to change our qualitative conclusions, they will be important for making precise quantitative predictions about the number density and composition of the first star clusters. We mention some of them below.

We assume in this paper that the internal structure of halos is unaltered between major merger events. However, it is possible for halos to increase their mass substantially through a succession of minor accretion events, and this will release gravitational potential energy and lead to heating (Yoshida et al. 2003; Reed et al. 2005). We intend to incorporate this in future work.

No attempt has been made to distinguish between star-formation and feedback in primordial star clusters and later generations. It is expected that the initial mass function should alter considerably once the metallicity reaches about  $10^{-3.5} Z_{\odot}$  (Bromm & Loeb 2003; Schneider et al. 2002; Santoro & Shull 2005) and that the spectrum of the ionization field would become softer and its normalisation lower.

We have neglected the effect of stellar winds and supernovae, both of which help to heat the surrounding gas and pollute it with metals. The effect of winds is fairly localised, but supernovae can lead to superwinds that expel enriched material from the star cluster. It is possible that this could affect neighbouring halos; more likely it will simply ensure thorough mixing of metals throughout a common parent halo. Numerical simulations will be required in order to model this process with any degree of realism.

Finally, it would be valuable as computing resources improve to simulate larger regions of space that would provide a more representative section of the Universe. This would allow us to distinguish between the early history of galaxies that are located within clusters and in mean density regions of space, for example. It would also allow for both localised feedback and a self-consistent build-up of the background, global radiation field.

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The appendix below describes how to go from cross-sections to reaction rates and heating terms.

## APPENDIX A: PHOTO-IONISATION AND PHOTO-DISSOCIATION INTEGRALS

The rate at which photo-ionisation or photo-dissociation reactions occur is given by:

$$k_i = 4\pi \int_{\nu_{\text{th}}}^{\infty} \sigma_{\nu,i} \frac{J_{\nu}}{h\nu} d\nu, \quad (\text{A1})$$

where  $h\nu_{\text{th}}$  is the threshold energy for which photo-ionisation (or photo-dissociation) is possible and  $\sigma_{\nu,i}$  is the frequency dependent cross-section of the  $i^{\text{th}}$  reaction. The cross-section and the threshold energies were taken from Table 1.  $J_{\nu}$  is the specific intensity given in Equation 4.

## APPENDIX B: HEATING TERMS

The energy per particle that a photon of energy  $h\nu$  transferred to an electron in an atom or ion is  $h\nu - h\nu_{\text{th}}$ . Therefore,

the energy per second per unit volume transferred to the gas (heating terms or heating functions) is:

$$\Lambda_{\text{heat},i} = 4\pi n_i \int_{\nu_{\text{th}}}^{\infty} \sigma_{\nu,i} J_{\nu} \frac{(\nu - \nu_{\text{th}})}{\nu} d\nu, \quad (\text{B1})$$

where  $n_i$  is the number density of the dissociated species.

The heating of a primordial gas comes primarily from photo-ionisation of H, He and  $\text{He}^+$ , but there is also a small contribution from photo-dissociation of  $\text{H}_2$ .